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Investigation of Transverse Motion of Concealed Scatterer Using Correlation of Speckled Speckles From Static Surface Layer

Gokul G. Nair ^a, Vinu R.V^b, Dinesh N. Naik^a, Michael Linde Jakobsen^c, Steen G. Hanson^c,
and Rakesh Kumar Singh^{a,d}

^aIndian Institute of Space science and Technology (IIST), Trivandrum-695547

^bCenter for Optical Research and Education (CORE), Utsunomiya University, Tochigi, 321-8585 JAPAN

^cDTU Fotonik, Department of Photonics Engineering, DK-4000 Roskilde, Denmark

^dDepartment of Physics, Indian Institute of Technology (BHU), Varanasi, Uttar Pradesh, India

ABSTRACT

Speckle-based techniques have noteworthy applications in the field of material science, surface characterization, determining mechanical displacements, biological activity in diffuse layer, imaging through turbid layer etc. The passage of coherent light through a diffuse layer generates a random speckle pattern, which have the inherent feature of carrying information associated with the diffuse layer. Dynamic laser speckle associated with the displacements of scattering surface has prominent impacts in the study of biological activity inside the diffuse layer. Investigations are progressing in the direction of exploring the dynamical properties associated with speckled speckles and its applications in imaging and characterization scenarios. In this work, we theoretically and experimentally study the dynamical properties of speckles through a static scattering layer using intensity correlation. The displacement (transverse or angular) produced in the concealed scatterer generates the dynamic speckle pattern which is observed through a second static diffuser. We expect to find applications of this investigation into the tracking objects hidden in the diffuse layer, measuring biological activity in diffuse layer, displacement measurements, etc.

Keywords: Speckle Correlation, Speckled Speckles, Velocity measurement, Bio Speckles, Imaging through turbid medium, Statistical Optics

1. INTRODUCTION

Speckle is a granular pattern that appears when highly coherent light is scattered by a random structure.¹ In contrast to efforts to suppress speckle to improve imaging quality, there have also been approaches to exploit speckle patterns as a means of gathering physical information about a target. This field of research, known as speckle metrology, enables the measurement of various physical quantities such as vibration, roughness, and velocity. At the same time, speckle has also been used to measure the optical characteristics of light, including wavelengths and images.² The use of granular structure named speckles that arise when coherent light is scattered from a rough surface and the intensity is probed has been extensively studied¹ When the scattering surface is undergoing a displacement, the observed speckle pattern, itself, will show dynamic properties. This fact has been used intensively for various applications.³ Of special interest for the present evaluation is the determination of velocity of structures buried in a diffuse medium, here modeled as an illuminated dynamic structure giving rise to speckle but buried behind a diffuse screen. The issue of speckled speckles has previously been addressed. Françon et al.⁴ have experimentally shown how minute displacements can be monitored, while Iwai and Asakura⁵ experimentally have investigated triply-scattered speckles for displacement measurement. Here, the incident light first passed a diffuser, after which the speckled light hit the dynamic structure, and the scattered light passed the first diffuser once more and was detected. Also in the case of laser eye safety, the issue of speckled speckles is of importance⁶. In early investigations of the phenomenon of speckled speckles, experiments

Further author information: (Send correspondence to Gokul G. Nair)

Gokul G. Nair: E-mail: gokulgnair77755@gmail.com, Telephone: +91-9495400121

were conducted, in which the object was displaced with a constant velocity, and the spectral temporal content of the doubly scattered light was examined, especially with respect to its correlation decay time,^{5, 7-12} In this case, the distinction between speckle decorrelation (“boiling”) and speckle displacement were mixed with the speckle size, giving little information on each individual component.

A specific reason for many of these investigations has been the investigation of optically based systems for probing subcutaneous blood flow. Ruth¹³ has very early shown how it is possible based on the dynamical speckled speckle pattern to provide information on the embedded blood flow. Of special interest in this evaluation was the exclusion of the speckle dynamics from the inadvertent movement of the skin, in order to enhance and separate the information from the blood flow. Later, investigations have been conducted showing measurements of blood flow^{14, 15} and for measuring skin thickness, as well.¹⁶

In the following, we will sketch the derivation of speckle size, decorrelation length, and gearing of speckle displacement with relation to object displacement in case of speckled speckles. Furthermore, we will present analytical expressions in case the two diffusers are separated by free space, and the speckles arising from the second, and static, diffuser are observed after propagation in free space. The expressions will cover both the near field and the far field. No polarization effects will be included. The experimental findings which support the analytical results are also included.

2. THEORETICAL DESCRIPTION

We begin with the theoretical formulation of speckled speckles using field propagation through a pair of scattering media. Referring to the geometry of Figure[1], suppose that a scattering medium (diffuser) is placed a distance z_1 in front of a positive lens and is illuminated by monochromatic light. We represent the complex field immediately behind the object by $U_0(\xi, \eta)$. At a distance z_2 behind the lens there appears a field distribution that we represent by $U_s(u, v)$. In view of linearity of the wave propagation phenomenon,¹ we can in all cases express the field U_s by the following superposition integral:

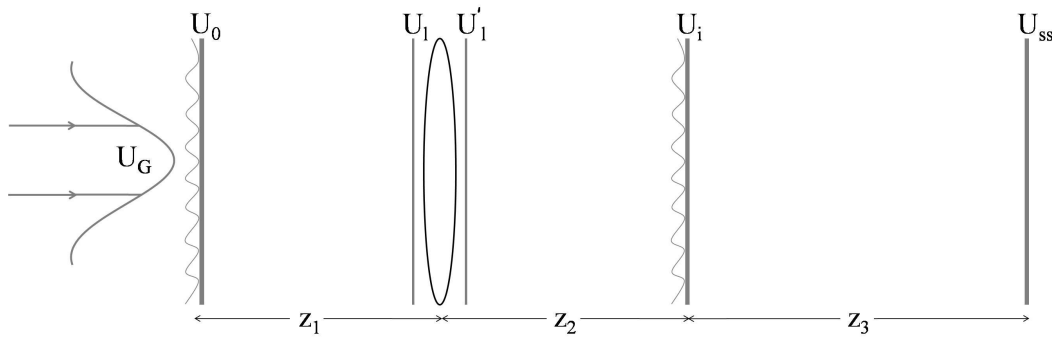


Figure 1. Geometry for formation of Speckled Speckles

$$U_s(u, v) = \iint_{-\infty}^{\infty} G_1(u, v; \xi, \eta) U_0(\xi, \eta) d\xi d\eta \quad (1)$$

where $G_1(u, v; \xi, \eta)$ is the Green's function connecting propagation between the first and second diffuser through an imaging lens.¹⁷ Thus the properties of the imaging system will be completely described if the Green's Function $G_1(u, v; \xi, \eta)$ can be specified. If the optical system is to produce high-quality images, then U_s must be as similar as possible to U_o . Equivalently, the impulse response should closely approximate a Dirac delta function,

$$G_1(u, v; \xi, \eta) \approx K \delta(u \pm M\xi, v \pm M\eta) \quad (2)$$

where K is a complex constant, M represents the system magnification, and the plus and minus signs are included to allow for the absence or presence of image inversion, respectively. We shall therefore specify as the "image plane" that plane where (2) is most closely approximated.

But, we know, $U_0(\xi, \eta)$ will be the complex field just after the first diffuser. Considering the Gaussian field as $U_g(\xi, \eta)$, $U_0(\xi, \eta)$ is given by,

$$U_0(\xi, \eta) = \iint_{-\infty}^{\infty} U_g(\xi', \eta') \exp[j\Phi(\xi', \eta')] \delta(\xi' - \xi, \eta' - \eta) d\xi' d\eta' \quad (3)$$

Now, to find the Green's function (G_1), let the object be a δ function (point source) at coordinates (ξ, q) . Then incident on the lens will appear a spherical wave diverging from the point (ξ, q) . The paraxial approximation to that wave is written,

$$U_l(x, y) = \frac{1}{j\lambda z_1} \exp\{j \frac{k}{2z_1} [(x - \xi)^2 + (y - \eta)^2]\} \quad (4)$$

After passage through the lens (focal length f), the field distribution becomes

$$U_l'(x, y) = U_l(x, y) P(x, y) \exp[-j \frac{k}{2f} (x^2 + y^2)] \quad (5)$$

Now, using the Fresnel diffraction equation to account for propagation over distance z_2 , we have,

$$G_1(u, v; \xi, \eta) = \frac{1}{j\lambda z_2} \iint_{-\infty}^{\infty} U_l'(x, y) \exp\{j \frac{k}{2z_2} [(u - x)^2 + (v - y)^2]\} dx dy \quad (6)$$

where constant phase factors have been dropped. Combining (3), (4), and (5), and again neglecting a pure phase factor, yields the formidable result

$$\begin{aligned} G_1(u, v; \xi, \eta) &= \frac{1}{\lambda^2 z_1 z_2} \exp[j \frac{k}{2z_2} (u^2 + v^2)] \exp[j \frac{k}{2z_1} (\xi^2 + \eta^2)] \\ &\times \iint_{-\infty}^{\infty} P(x, y) \exp[j \frac{k}{2} (\frac{1}{z_1} + \frac{1}{z_2} - \frac{1}{f}) (x^2 + y^2)] \\ &\times \exp\{-jk[(\frac{\xi}{z_1} + \frac{u}{z_2})x + (\frac{\eta}{z_1} + \frac{v}{z_2})y]\} dx dy \end{aligned} \quad (7)$$

Speckled Speckles generated at Observation plane U_{ss} can be related to the Speckled field U_s using another Green's function G_2 . Where G_2 is defined as,

$$G_2(\alpha, \beta; u, v) = \frac{1}{j\lambda z_3} \exp\{j \frac{k}{2z_3} [(\alpha - u)^2 + (\beta - v)^2]\} \quad (8)$$

Finally, using the Fresnel diffraction equation to account for propagation over distance z_3 , we will get

$$U_{ss}(\alpha, \beta) = \frac{1}{j\lambda z_3} \iint_{-\infty}^{\infty} U_s(u, v) \exp\{j \frac{k}{2z_3} [(\alpha - u)^2 + (\beta - v)^2]\} du dv \quad (9)$$

This gives the general information about the propagation. So, at the observation plane we get the intensity distribution I_{ss} of complex field U_{ss} as speckled speckles.

$$I_{ss}(\alpha, \beta) = |U_{ss}(\alpha, \beta)|^2 \quad (10)$$

According to the experimental scheme in Figure [2], the following can be substituted.

$$z_1 = 2f \quad (11)$$

Also, at exact imaging condition, where Equation [2] is valid,

$$\begin{aligned} z_2 &= 2f \\ z_3 &= l \end{aligned} \quad (12)$$

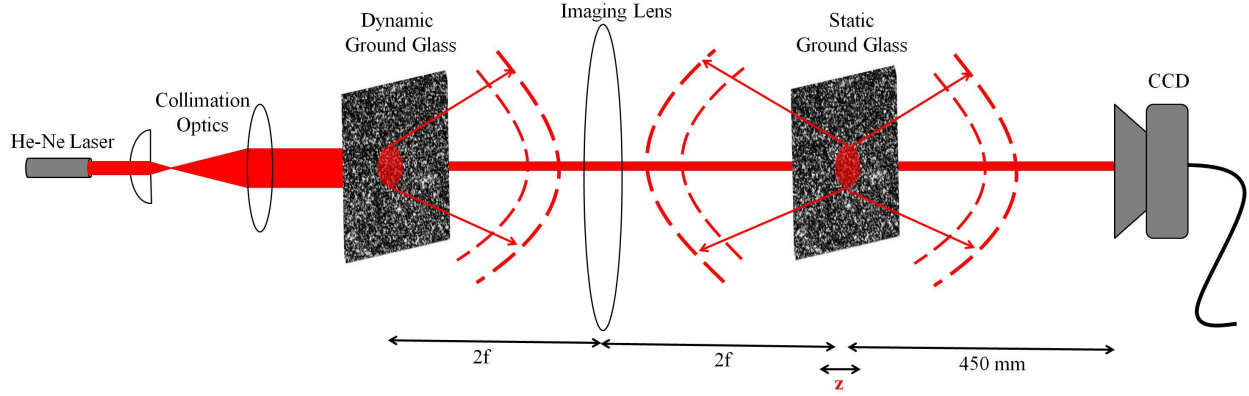


Figure 2. Experimental Scheme

In all other cases they will satisfy,

$$z_2 + z_3 = \text{Constant} = L = 2f + l \quad (13)$$

Now, for the experiment we will vary z_2 as $2f \pm \Delta z$ and which will lead to $z_3 = l \mp \Delta z$. This will always satisfy the Equation [13] for z_2 and z_3 . Note that, Δz will be zero at the imaging condition.

For each value of Δz , we will now move the first diffuser in lateral direction in steps of $\Delta \xi$. Remember the fact that the co-ordinate system will not shift here, but only the diffuser.

The new random phase introduced at each step by the shifting of diffuser is represented by,

$$\Phi(\xi, \eta) = \Phi_R(\xi - \Delta \xi, \eta) \quad (14)$$

Where, $\Phi_R(\xi, \eta)$ is phase distribution of the first scatterer at $\Delta \xi = 0$. Then equation [3] changes as,

$$U_0(\xi, \eta) = \iint_{-\infty}^{\infty} U_g(\xi', \eta') \exp[j\Phi_R(\xi' - \Delta \xi', \eta')] \delta(\xi' - \xi, \eta' - \eta) d\xi' d\eta' \quad (15)$$

Next, processing of the Speckled Speckles will takes place. We will execute intensity cross correlation of the resulting images. For each values of Δz all the images with $\Delta \xi$ shift will be correlated with the reference image, which is taken when $\Delta \xi = 0$.ie,

$$C(\Delta \xi, \Delta z) = \langle \Delta I_{ss}(\alpha, \beta, \Delta \xi = 0, \Delta z) \Delta I_{ss}(\alpha, \beta, \Delta \xi, \Delta z) \rangle \quad (16)$$

$C(\Delta \xi, \Delta z)$ is defined as the cross correlated output of the images in the observation plane.

$$C_R(\Delta \xi, \Delta z) = \langle \Delta I_{ss}(\alpha, \beta, \Delta \xi = 0, \Delta z) \Delta I_{ss}(\alpha, \beta, \Delta \xi = 0, \Delta z) \rangle \quad (17)$$

$C_R(\Delta \xi, \Delta z)$ is the autocorrelated function of the Reference Intensity at $\Delta \xi = 0$. Now, we will define P as the position of peak intensity in the correlation output. Therefore, ΔP will be,

$$\Delta P = P - P_R \quad (18)$$

P_R will be the position of the peak intensity in $C_R(\Delta \xi, \Delta z)$. Since each value of $\Delta \xi$ offers a corresponding ΔP , we define the slope of graph plotted between ΔP and $\Delta \xi$ as Speckle Gearing, G_s .

$$\text{Speckle Gearing, } G_s = \frac{\Delta P}{\Delta \xi} \quad (19)$$

3. EXPERIMENTAL ANALYSIS

Using the scheme explained above, we conducted a series of experiments. The lens was having a focal length f of 100 mm and l was taken as 450 mm. z_2 has been varied as $z_2 \pm \Delta z$ where, Δz ranges from -5 mm to +20 mm. (Here distances toward the lens from the second diffuser is taken as negative). For each value of Δz the dynamic diffuser is varied from -65nm to $+65\text{nm}$.

Each set of readings will be recorded for each value of Δz . Now, we will perform the intensity correlation of the Image field, for each image with respect to the reference image. The intensity correlation images are given in Figure 3.

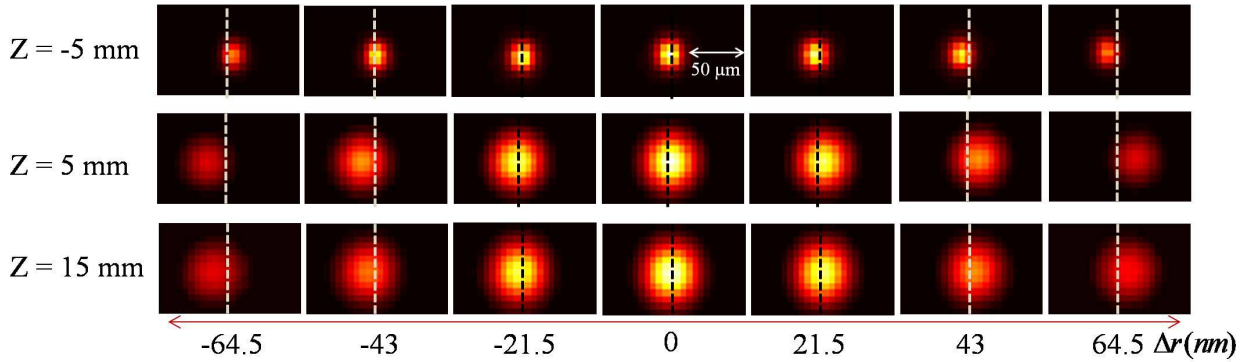


Figure 3. Cross Correlation of Image Intensities

The shift in the peak intensity position as well as decorrelation is visible from Figure [3]. The same trend continues for all values of Δz . Now we will plot graph between ΔP and $\Delta \xi$. The slope of the graph, ie. the speckle gearing is derived for each case.

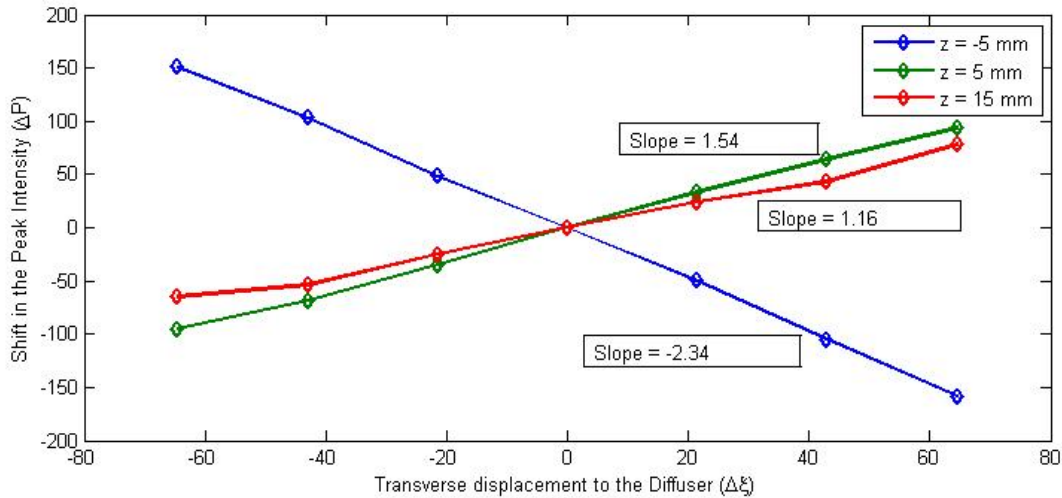


Figure 4. Graph plotted between $\Delta \xi$ and ΔP (Both are in nm)

As per the generalised ray- matrix formulation, when B_1 equals zero, the image of the first diffuser coincides with the second diffuser, and the gearing becomes zero.¹⁷ Accordingly, this corresponds to a z -value of 2.2 mm. The decorrelation of the speckles revealed through decreasing intensity of peaks though remains similar, the correlation width varies as a function of z . Most importantly, the speckle gearing provides the depth information as well as the flow of the concealed dynamic diffusing layer.

4. DISCUSSION

The expressions for speckle dynamics have been derived and verified experimentally. The parameters such as Speckle size, Speckle Gearing are obtained in both methods. Since the far field propagation geometry is involved slight changes will be introduced to the equations when variations in the distance appear, which will lead to violation of Equation [2].

The results prove that using these properties depth information can be obtained, which will have application in flow measurements inside a diffuse layer. Furthermore, the investigation is important when we measure the blood flow in tissue, where scattering from the skin surface will act as the static diffuser and blood will act as the dynamic diffuser. However, in all the applications the Speckle size and Gearing will depend upon the distance between two surfaces and the motion of dynamic diffuser as well.

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